HYBRID OF P3HT AND ZnO@GO NANOSTRCTURED PARTICLES FOR INCREASED NO2 SENSITIVITY

by
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Abstract

The NO_2 sensing properties and operational mechanism of the hybrid formed from poly(3-hexylthiophene) (P3HT) and zinc oxide-graphene oxide (ZnO@GO) nanoparticles were investigated. We prepared graphene oxide (GO) and zinc oxide (ZnO) core-shell nanostructured particles with ionic aggregation. Gas sensors were fabricated by spin coating a mixture of P3HT with ZnO@GO on oxide-coated silicon wafers leading to formation of organic field-effect transistors (OFETs). The NO_2 sensing properties of the obtained devices were investigated at room temperature. By means of observing conductance changes before and after exposure to NO_2, it was demonstrated that the hybrid of P3HT with 60 wt% ZnO@GO composites exhibits 210% sensing response to 5ppm NO_2 gas exposure for 5min at room temperature. The sensing mechanism included a contribution from the hybrid that was not observed from pure P3HT or by adding either ZnO or GO alone.

Advisor: Dr. Howard E. Katz

Acknowledgement

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1.Introduction

Nitrogen dioxide (NO2) is well known as a poisonous and corrosive gas, harming the environment and causing health disorders. With the development of industry and transportation systems, NO2 has been mass produced and released into the environment mostly as a result of fuel combustion.1-6 Therefore, the detection and control of NO2 in the environment are crucial.

Graphene oxide (GO) and single-wall carbon nanotubes (SWNTs) have long been attractive as two-dimensional and one-dimensional materials respectively for carbon-based electronics and are also promising for chemical sensors because of their high carrier mobility, promoting easy observation of changes in resistance after exposure to analyte gas.6-8 Furthermore, Seivama et al.9 demonstrated that the electrical conductivity of ZnO can be significantly changed by the reactive gases in the air and thus the applications of various sizes and shapes of ZnO nanoparticles or nanowires as chemical gas sensors have been widely studied, among other metal-oxide semiconductors.10-13

The sensing mechanism of ZnO NPs and GO is based on the assumption that NO2 can induce hole density or electron traps.7 ZnO as an n-type semiconductor has a larger electron concentration than hole concentration. When ZnO is exposed to NO2, the decrease of conductivity of ZnO can be explained by electron trap formation. In the meantime, residual epoxy and carboxylic groups in GO act as electron withdrawing groups, promoting hole conduction, which is increased on exposure to NO2.

Recent work on using a combination of reduced graphene oxide (rGO) and ZnO for NO2 gas sensors was published by Galstyan et al.14 In their research, nanostructured ZnO was grown on an Al2O3 substrate and then a GO homogenous dispersion was drop cast onto the ZnO. It was demonstrated that the response of their rGO/ZnO to 5 ppm NO2 at 250℃ was 680%, and showed better sensing performance compared to pure ZnO. However, their fabrication method would likely result in heterogeneous distributions of the rGO and ZnO. If spin-coating of a mixture of the two had been used, the films would still have been non-uniform because centrifugal force would separate ZnO and rGO due to their different densities .

In our work, we utilize an ionic self-assembly method to synthesize ZnO@GO nanostructured particles (NPs), keeping the distribution of the two components uniform in composites. The ZnO NPs were directly positively charged by using (3-aminopropyl) trimethoxysilane (APS). When mixed with GO, the negative charge of residual carboxyl groups on GO will interact with positively charged surfaces of ZnO NPs, resulting in GO attaching and encapsulating ZnO NPs so that they are not separated by centrifugal force. (Fig. S1)

Due to the high responsiveness of ZnO and GO, their mixtures are attractive for sensors, as shown in Table 1. Liu et al.22 reported that ZnO-rGO nanocomposites show a sensing response towards 5 ppm NO2 of up to 25.6% at room temperature. Using other oxide materials, it was reported by Li et al.24 that p-n heterojunctions made from SnO2-SnO enable detection of NO¬2. SnO2 nanoparticles were loaded on SnO nanosheets on a

ceramic plate, and showed 19.1% sensing response toward 100 ppm NO2 at 50℃ temperature.

Organic field-effect transistor (OFET) sensors have advantages of high room temperature sensitivity, low commercial cost, mass production and mechanical flexibility.15 Therefore, many researchers focus on improving OFET sensing properties by forming blends and hybrids of high conductivity polymer and inorganic particles, because the pores and interfaces created by resulting heterojunctions enable gaseous molecules to easily penetrate into the polymer structure and be adsorbed by the nanostructured inorganic materials resulting in high sensitivity.4,16 Recent work reported by Xie and his co-workers17 utilized P3HT as semiconductor to fabricate OFET devices as NO2 gas sensors. It is shown that different thicknesses of P3HT employed in OFET devices have different sensing prosperities and the highest sensitivity can reach 120% to 5% NO2 with thicker film than pure P3HT at room temperature and the sensing properties are almost the same as our pure P3HT with similar thickness (Table 1). In addition, the mechanism of P3HT detection of NO2 gas is doping P3HT by the oxidizing NO2. Prakash et al.11 took advantage of a hemin/ZnO-polypyrrole (PPy) nanocomposite for NOx gas detection devices. The results are reported in the form of change in resistance with respect to time. The improvement of hemin/ZnO-PPy on Pt electrodes is 3-fold-enchanced sensitivity toward detection of NOx when comparing to hemin/PPy on Pt electrodes.

2.Experimental Section

2.1Materials Preparation

ZnO nanoparticles were synthesized by following a procedure reported by Alessio Becheri and his co-workers.19 This method has advantages of facile synthetic steps and large scale production in a short reaction period. Typically, 5.5 g of ZnCl2 (Sigma-Aldrich) was dissolved in 300 mL deionized water at 90℃ oil bath temperature and then 3.6 g of solid NaOH (Fisher Scientific) dissolved in 100 mL water was added into ZnCl2 solution. With appropriate stirring during a period of 1 h at 90℃ temperature, the synthesized ZnO nanoparticles were separated from the supernatant by sedimentation and washed with deionized water ten times in order to lower the concentration of NaCl. Finally, the particles were collected by centrifugation at 2,000 rpm for 30 min and dried in a vacuum oven to obtain ZnO NPs as a powder. In order to modify the ZnO NPs surface, ZnO NPs (300 mg) were dispersed in water by sonicating, then 1 mL (3-aminopropyl) trimethoxysilane (APS, Sigma-Aldrich) was added at 80℃ oil bath temperature. The washing and collection of ZnO-NH2+ NPs were carried out in the same way as ZnO NPs. Graphene oxide (GO) powder was bought from Sigma-Aldrich (15-20 monolayer sheets). The obtained ZnO (140 mg) and GO (60 mg) were dispersed in 200 mL and 50 mL deionized water, respectively and then the two well-dispersed solutions were mixed. The solution was adjusted to pH≈6 and stirring was continued for 1 h.20 The washing and collection procedure of ZnO@GO NPs were the same as for ZnO NPs, but with methanol as solvent.

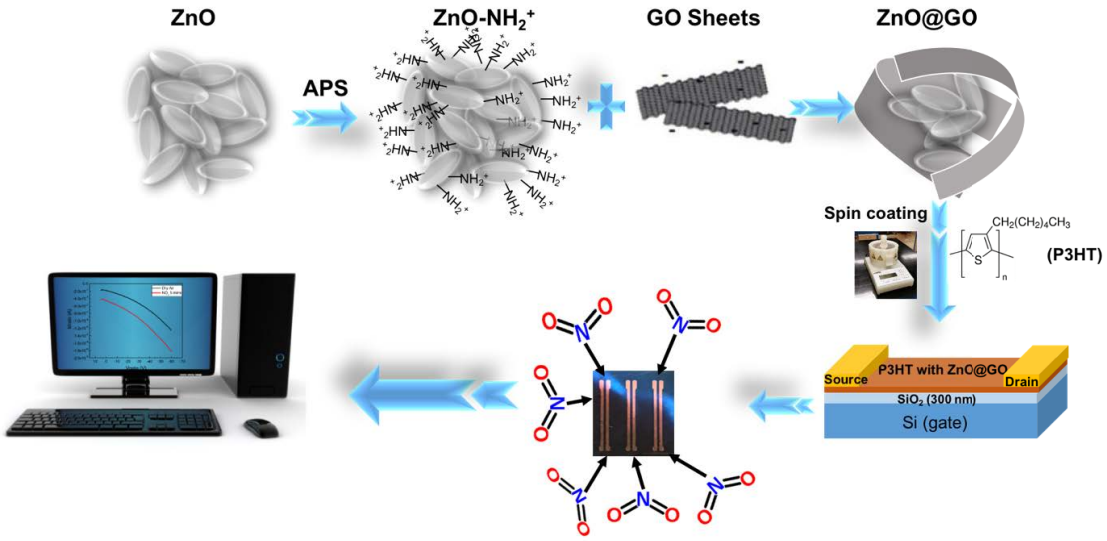
2.2Materials Characterization

The morphologies and EDAX spectra of the ZnO@GO were characterized by scanning electron microscopy (SEM, JEOL JSM-6700F). Meanwhile, the morphologies of organic field-electric transistor (OFET) sensor devices were investigated by atomic force microscopy (AFM, Dimension 3100 with a V Controller). Finally, the OFET properties and gas sensing properties of the materials were investigated by using a probe station and a Keysight Agilent 4155C analyzer.

2.3 Fabrication and functional characterization

Fig.1 is a schematic illustration of the device fabrication procedure. The obtained ZnO@GO composites were first dispersed in chlorobenzene (Sigma-Aldrich) with concentration of 10 mg/mL in 20 mL vials with sonicating, and poly(3-hexylthiophene) (P3HT, Sigma-Aldrich, Mw=15,000~45,000) was also dissolved in chlorobenzene with concentration of 10 mg/mL with stirring and heating. Afterwards, ZnO@GO composites with weight fraction from 0 to 60% were made under sonicating by mixing various volumes of ZnO@GO solution and P3HT solution. Highly p-doped silicon wafers with 300 nm thermally grown oxide were diced into 1 in. × 1 in. substrates, cleaned by immersing in piranha solution more than half hour, sonicated in isopropanol and acetone sequentially, and then dried by using forced nitrogen gas. The substrates were further modified by exposing to hexamethyldisilazane (HMDS, Sigma-Aldrich) vapor at 100 °C for 2 h in a loosely sealed vessel.9 The obtained hybrids of P3HT with different weight fraction of ZnO@GO composites were spin coated on as-prepared substrates. The samples were annealed at 120 °C for 3 h prior to evaporating 50 nm gold on top of the

samples as source and drain OFET electrodes. Gas sensing properties were investigated by means of the flow-through technique at atmospheric pressure, using an Environics Gas Dilution Gas System (Series 4040) with 5-ppm nitrogen dioxide in dry air.21 A sealed 135 ft3 cylinder (Praxair, Co.) with certified NO2 concentration 48.8 ppm allowing continuous flow was used for NO2 exposure experiments. The gas sensing behavior of the samples was investigated on a silicon wafer of the Agilent 4155C semiconductor analyzer at room temperature under ambient conditions by pressing the sample firmly with source, drain and gate probes. The setup voltage of probes is 0 V, -60 V, 0~-60V sweeping, corresponding to source probe, drain probe and gate probe.



Scheme 1:A scheme to illustrate the preparation of ZnO@GO nanoparticles and NO2 gas sensor

3.Results and Discussion

The morphologies of obtained ZnO NPs, GO and ZnO@GO NPs were first characterized by scanning electron microscopy (SEM) with a 10 kV focused electron

beam.In Fig.1a, the SEM image of ZnO clearly shows the obtained ZnO nanoparticles have ellipsoid shapes with major axis and minor axis having length of 240 nm and 130 nm, respectively. The SEM image of GO (Fig. 1b) shows the multilayer of GO. It is seen that GO exhibits plate-like morphology formed by the aggregation of GO because of the strong π-π stacking interaction between GO sheets. Fig. 1c and its backscattering image (Fig. 1d) confirm the structure of ZnO@GO nanostructured composite. Since GO has much higher conductivity than ZnO, the electron beam in the backscattering mode will go through the GO sheets making GO more transparent than the ZnO, and the resulting image (1d) is therefore less intense.

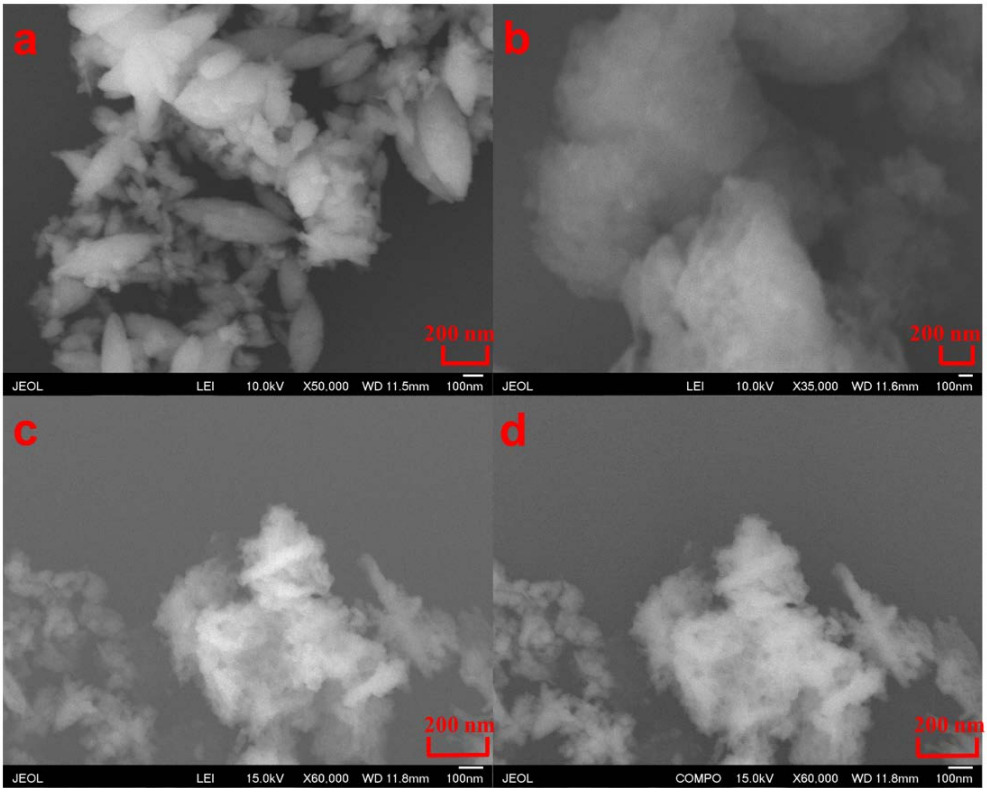


Figure 1：a SEM image of ZnO nanoparticles. b SEM image of GO. c SEM image of ZnO@GO composite. d Back scattering image of c.

The composition of ZnO@GO nanoparticle composites was characterized by the EDAX mapping. As shown in Fig. 2, the ZnO@GO NPs are composed of C, O, Zn elements, consistent with both GO and ZnO being together in the particles. In addition, the peak of Si and Mg elements in EDAX mapping can be regarded as the glass substrate on which ZnO@GO NPs sample was prepared.

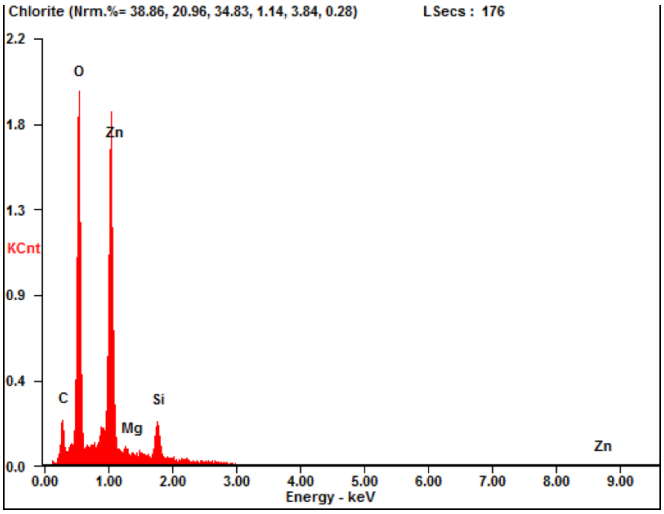


Figure 2：EDAX Spectrum of ZnO@GO nanoparticles on glass substrate

In our study, all the sensor devices showed p-type doping response behavior upon the exposure to NO2 at room temperature. After exposure to NO2, the conductivity of sensors could increase significantly. As shown in Fig. 3, the transfer and output curves of OFETs correspond to the typical p-type semiconductor curve with on/off ratios of 10 with near-saturation. Furthermore, OFET properties of other devices are shown in Fig. S2 and Fig. S3.

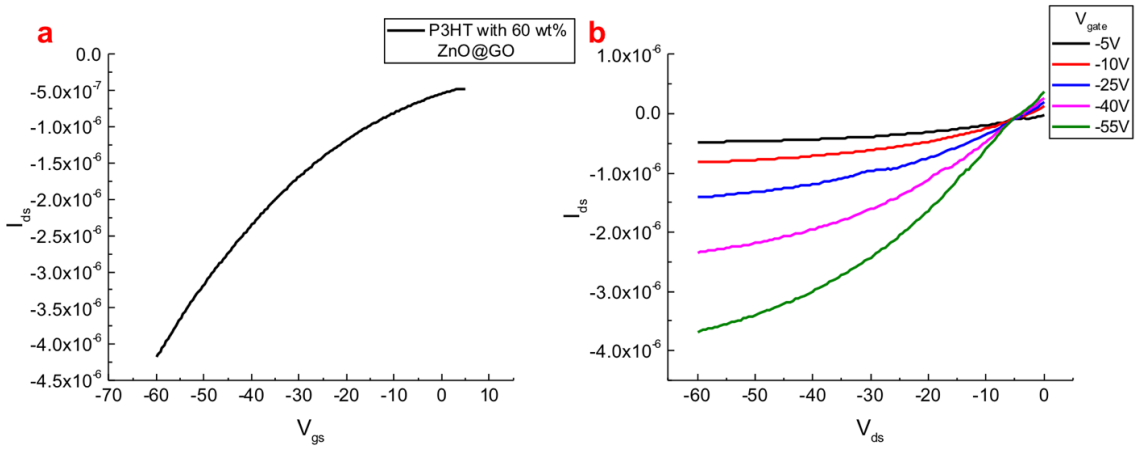


Figure 3：Typical OFET properties characterization of hybrid of P3HT with 60 wt% ZnO@GO, a Transfer curve; b Output curve

The responses of the devices to NO2 gas are shown by plotting change in drain current versus exposures. Sensitivity is defined in this work as S=100%×(I_ds-I_ds^i)/I_ds^i,9 where I_ds is the drain current measured at gate voltage (V_gs) and drain voltage (V_ds) are both -60 V after exposure to NO⁻2 gas and I_ds^i is initial stable current in dry air with V_gs and V_ds both at -60 V. We obtained these data for various weight fractions of ZnO@GO in composites.

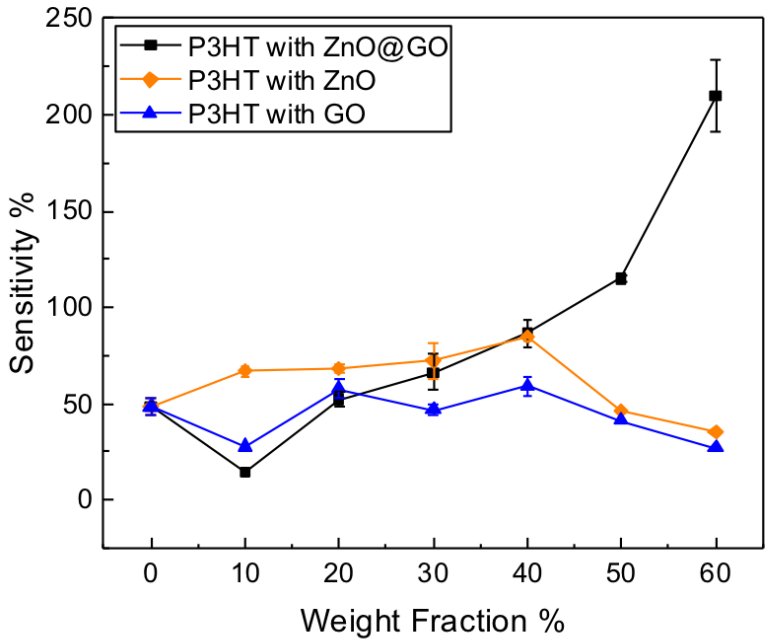


Figure 4：The sensitivity of the sensors versus weight fraction of inorganic particles under 5 ppm for 5 min.

As shown in Fig. 4, the sensitivity of pure P3HT is 48% at room temperature. Apparently, the sensing response to NO2 is almost the same as previous work by Xie et. al.17 Notably, with the increase of the weight fraction of ZnO@GO composite NPs, the sensitivity first decreases slightly and then increases much more. The 10 wt% ZnO@GO causes disruption that dominates the electronic behavior relative to any effects of NO2. Furthermore, 20 wt% of ZnO@GO NPs reached nearly the same sensitivity as pure P3HT. The particles are involved in disruption of polymer morphology as well, but with increasing weight fraction of particles, the conductance mechanism is no longer dominated by the disruption but rather by a mechanism that is sensitive to NO2. At 60 wt% ZnO@GO composite, the sensitivity has a rapid increase to 210%.

Fig. 4 also reports the sensitivity of the hybrid of P3HT and ZnO NPs with respect to the weight fraction of ZnO NPs. At the range of 0~40 wt% of ZnO, the sensitivity is essentially the same as for pure P3HT, and at 50 and 60 wt% of ZnO the sensitivity decreases compared to previous weight fractions. For large weight fractions of ZnO, ZnO is making an opposite sign contribution to electrical conductivity change compared to P3HT, resulting in decrease of sensitivity of hybrid devices. Fig. 4 also indicates that the sensitivity of hybrid of P3HT and GO has a wave-like curve with respect to the weight fraction of GO but which is not outside the bounds of the standard deviations.

Because the sensing mechanism of P3HT or its composites with only ZnO or GO cannot explain the sensing behavior of the hybrid of P3HT with ZnO@GO, atomic force microscopy (AFM) was used as a morphology investigation method of the hybrid of P3HT and ZnO@GO. Fig. 4 shows the AFM image of hybrid of P3HT and ZnO@GO composites before exposure to NO2 (a, b) and after exposure to 5 ppm NO2 for 5 min (c, d). It is seen that the apparent volume fraction of ZnO@GO is much larger than the volume fraction of ZnO or GO (Fig. S4) at the same weight fraction, leading to short distances between particles indicating a possible nearly-connected GO network illustrated by the red lines and white dashes in Fig. 4d. Hence, after exposure to NO2 for 5 min, although the volume fraction within the same surface area does not show apparent change, the doping effect of NO2 on P3HT that is immediately adjacent to particles reduces its resistance and thus bridges particles helping GO form a continuous network. However, it is observed by AFM that the distances of P3HT between the other particle clusters (ZnO or GO) are much longer than the case of P3HT with ZnO@GO. Therefore, when considering the long distance between inorganic particles, P3HT cannot be regarded as

bridge in these cases because the doping effect of NO2 on this more bulklike P3HT would only lead to 48% change in conductivity.

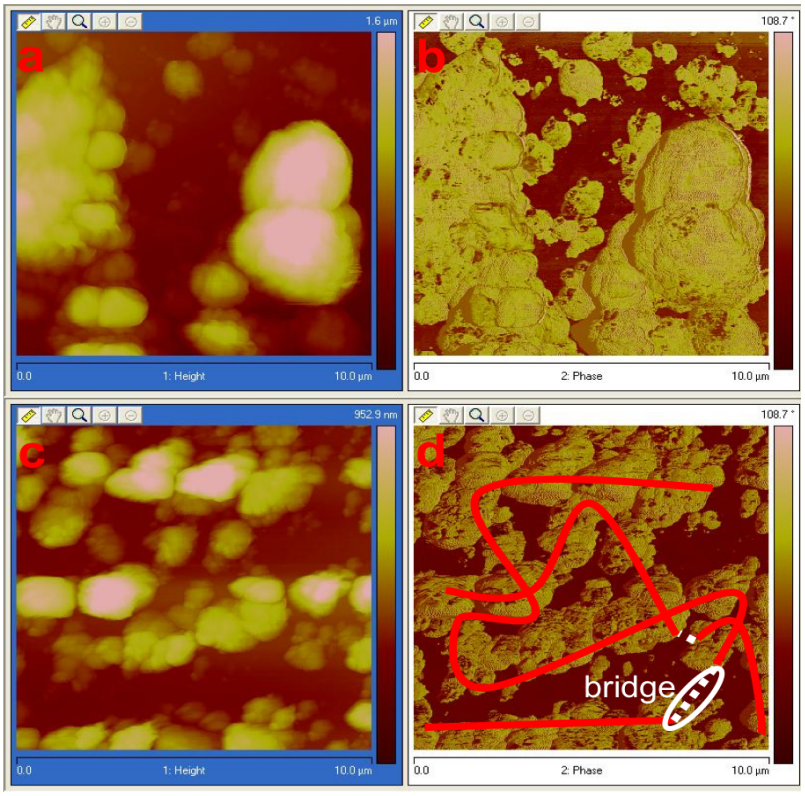


Figure 5：AFM image of P3HT with 60 wt% ZnO@GO: a and b are height image, phase image before exposure to NO2 gas, respectively; c and d are height image, phase image after exposure to 5 ppm NO2 gas for 5 min, respectively.

The responses of the sensors toward various times of gas flowing for 5 ppm NO2 and various concentrations of NO2 for 5 min are also examined. As shown in Fig. 5a, the sensitivity increases with increasing exposure time at room temperature. Fig. 5b shows the response curve of the sensor based on P3HT with 60 wt% ZnO@GO hybrids toward various concentrations of NO2. It is seen that the conductance of the sensor increases

with increasing concentrations. Furthermore, it is shown that the device has 32% sensitivity even when the NO2 concentration is as low as 1 ppm. In addition, the highest response appears when exposure time and concentration are 5 min, 5 ppm respectively.

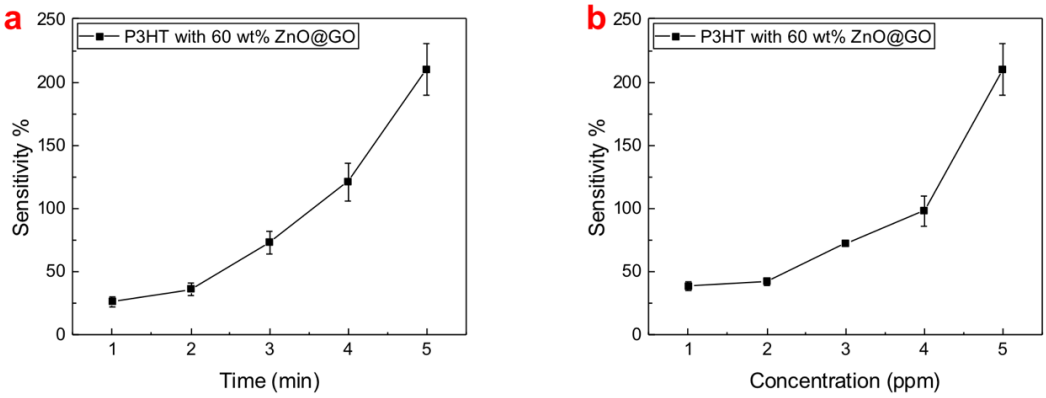


Figure 6：Sensitivity of hybrid of P3HT and 60 wt% ZnO@GO composites with respect to a exposure time under 5 ppm NO2 exposure concentration, b exposure concentration of NO2 for 5 min

The novelty of present work is the introduction of organic-inorganic hybrid NPs and OFET devices and high response at room temperature, even though P3HT or ZnO/GO-based sensors have been studied individually before. Table 1 reports the comparison of previous results on NO2 sensors similar to this work. It is seen that typical fabrication of NO2 sensor uses silicon, ceramic and aluminum substrates. The high temperature improves the adsorption/reaction process of NO2 and thus increases the response of materials.14 In comparison to other work, NO2 -sensitive devices in this work have the advantage of high response to NO2 at low concentration of NO2 when operating at room temperature.

Table 1：Response to NO2 reported in previous work and comparison of this work

Materials	Operating Temperature (℃)	Concentration (ppm)	Response %	Device	Ref.
ZnO-rGO	Room Temperature	5	25.6	Dip-coating on ceramic substrate	22
ZnO-rGO-Au	80	100	32.55	Droping on ceramic substrate	1
Graphene/ZnO	200	5	36.7	OFET	11
RGO/ZnO	25	5	＜1	Spraying on gold interdigital electrodes	24
RGO/ZnO	250	5	680	Growing on aluminum substrate	14
P3HT	Room Temperature	5	38	OFET (170-200 nm film)	17
			120	OFET (550-600 nm film)	
P3HT-ZnO@GO	Room Temperature	5	210	OFET	This work
		1	32		

4.Conclusion

The gas sensing properties of hybrid of P3HT and ZnO@GO composite materials as semiconductors in OFETs were investigated for the detection of nitrogen dioxide (NO2). The sensing response of the hybrid P3HT-ZnO@GO composites is much higher than pure P3HT and the device can reach 210% sensing response under the condition of 5 ppm NO2 and 5 min exposure time. The devices operate at room temperature, and the sensitivity of the device increases with increasing weight fraction of ZnO@GO composites. In addition, the sensing response has been investigated versus exposure time and NO2 concentration independently. It is seen that the increase of exposure time and NO2 concentration leads to higher sensing response. By occupying more volume fraction than same weight fraction of ZnO or GO, ZnO@GO composites form a network where NO2 can dope the P3HT bridges to increase the connectivity and thus the conductivity. To the best of our knowledge, this is the first report of the use of P3HT and ZnO@GO composites as organic-inorganic hybrid materials in an OFET device configuration and

provides the most sensitive semiconductor-based NO¬2 detection at room temperature yet reported.

Reference

Appendices

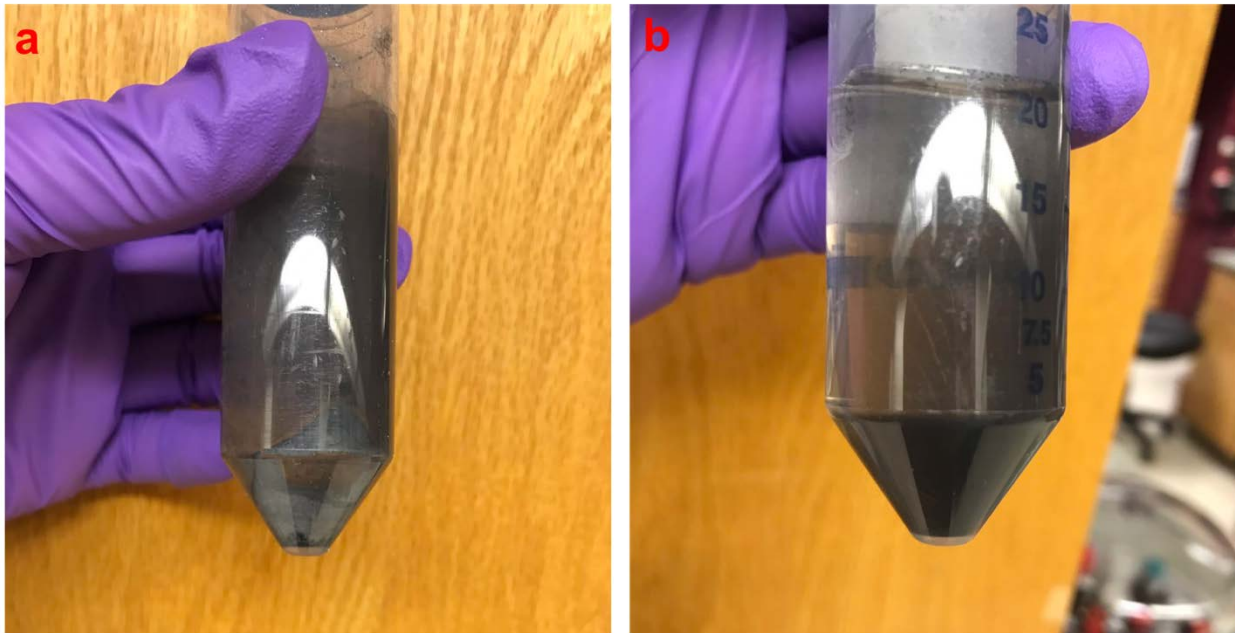


Fig. S1. Photos of materials after 30 min centrifuge, a ZnO and GO simply mixed by sonicating; b ZnO@GO composites obtained by ion self-assembly method.

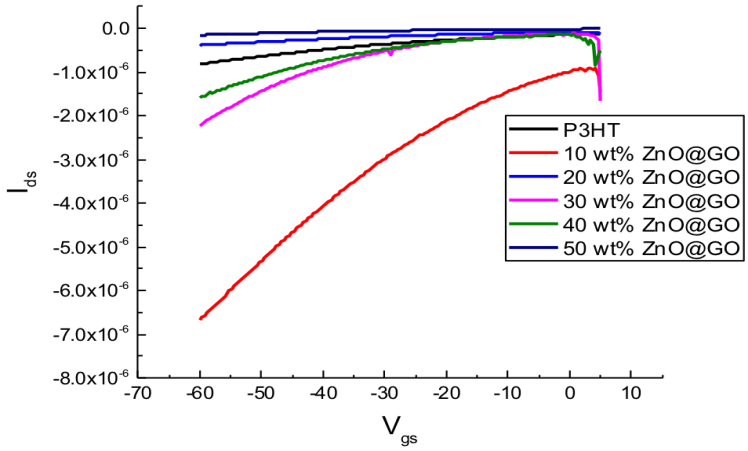
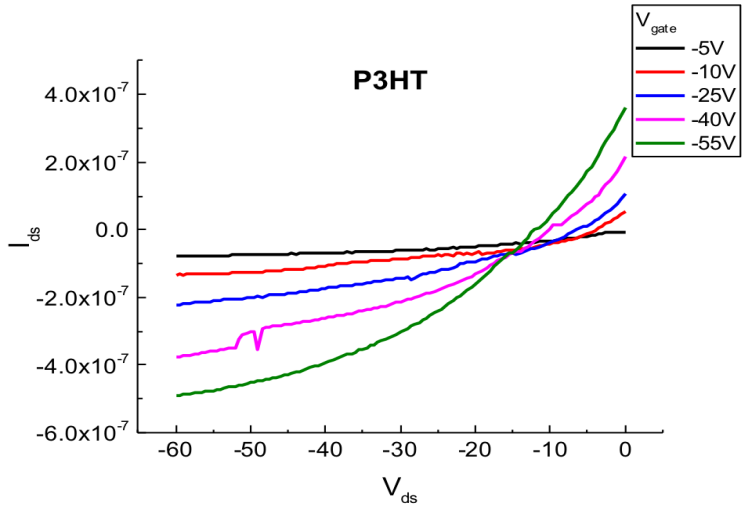
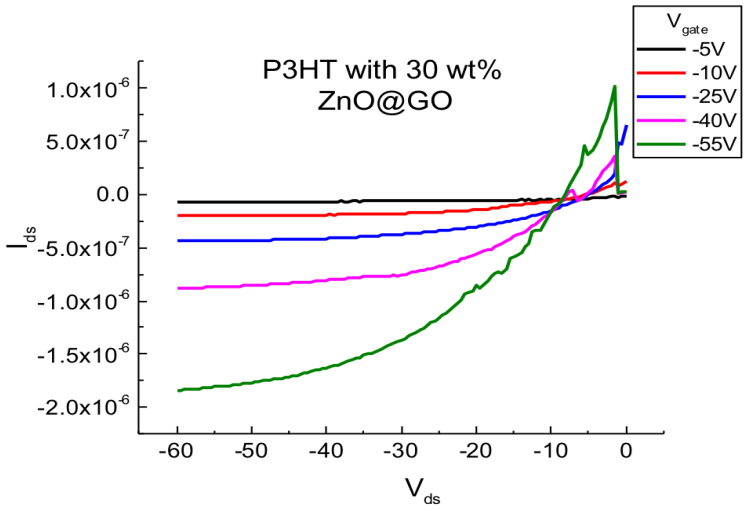
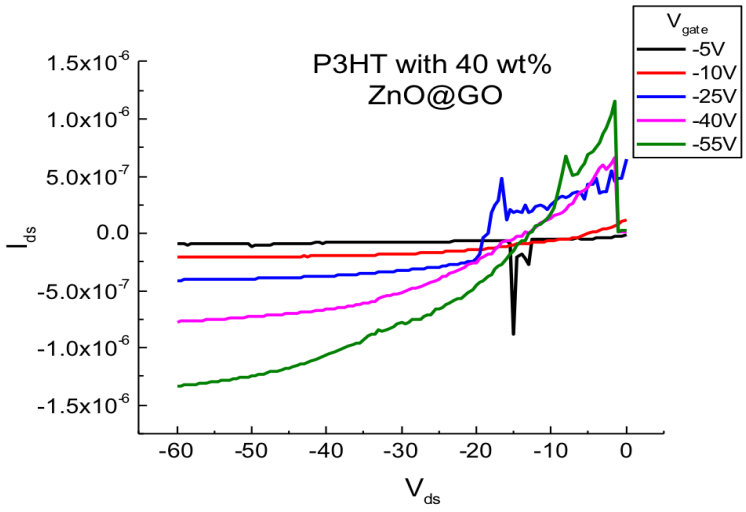


Fig. S2. Typical organic field effect transistor transfer curve of P3HT and hybrid P3HT with various weight fraction of ZnO@GO




P3HT with 30 wt%
ZnO@GO
V gate
-5V
-10V
-25V
-40V
-55V
1.0x10-6
5.0x10-7
0.0
-5.0x10-7
-1.0x10-6
-1.5x10-6
-2.0x10-6
Ids
-60
-50
-40
-30
-20
-10
0
Vds


P3HT with 40 wt%
ZnO@GO
V gate
-5V
-10V
-25V
-40V
-55V
1.5x10-6
1.0x10-6
5.0x10-7
0.0
-5.0x10-7
-1.0x10-6
-1.5x10-6
Ids
-60
-50
-40
-30
-20
-10
0
Vds

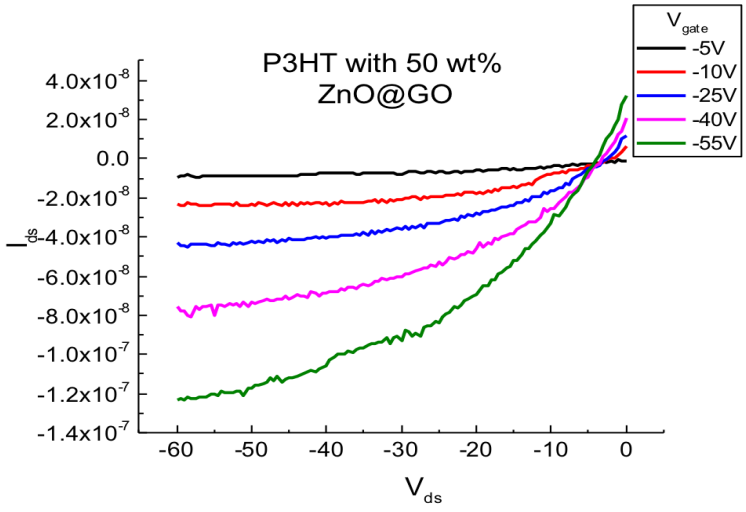
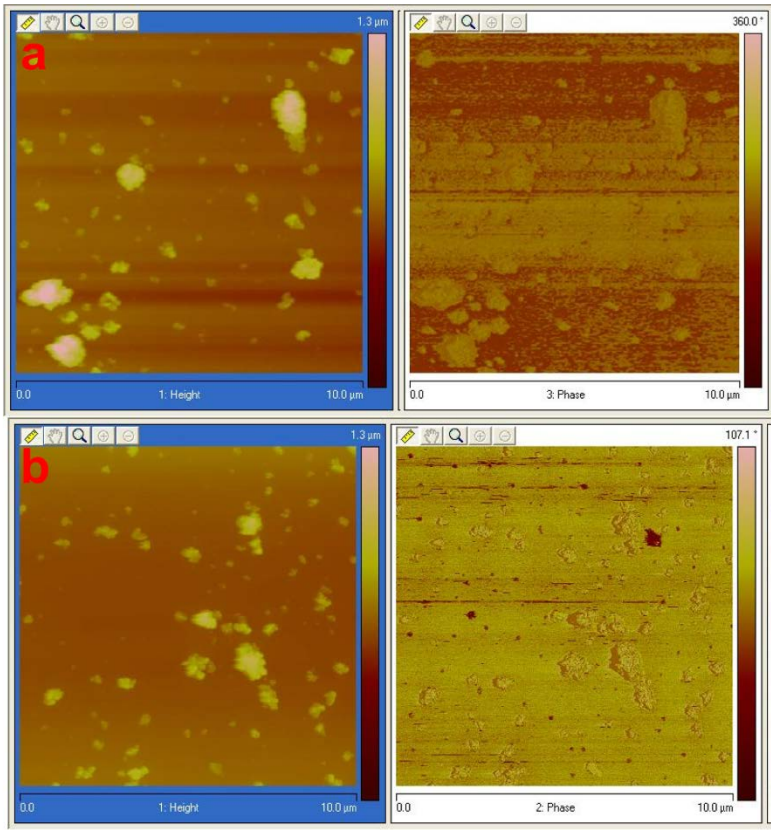

P3HT with 50 wt%
ZnO@GO
V gate
-5V
-10V
-25V
-40V
-55V
4.0x10-8
2.0x10-8
0.0
-2.0x10-8
-4.0x10-8
-6.0x10-8
-8.0x10-8
-1.0x10-7
-1.2x10-7
-1.4x10-7
Ids
-60
-50
-40
-30
-20
-10
0
Vds

Fig S3. Typical organic field effect transistor output curves of P3HT and hybrid P3HT with various weight fraction of ZnO@GO



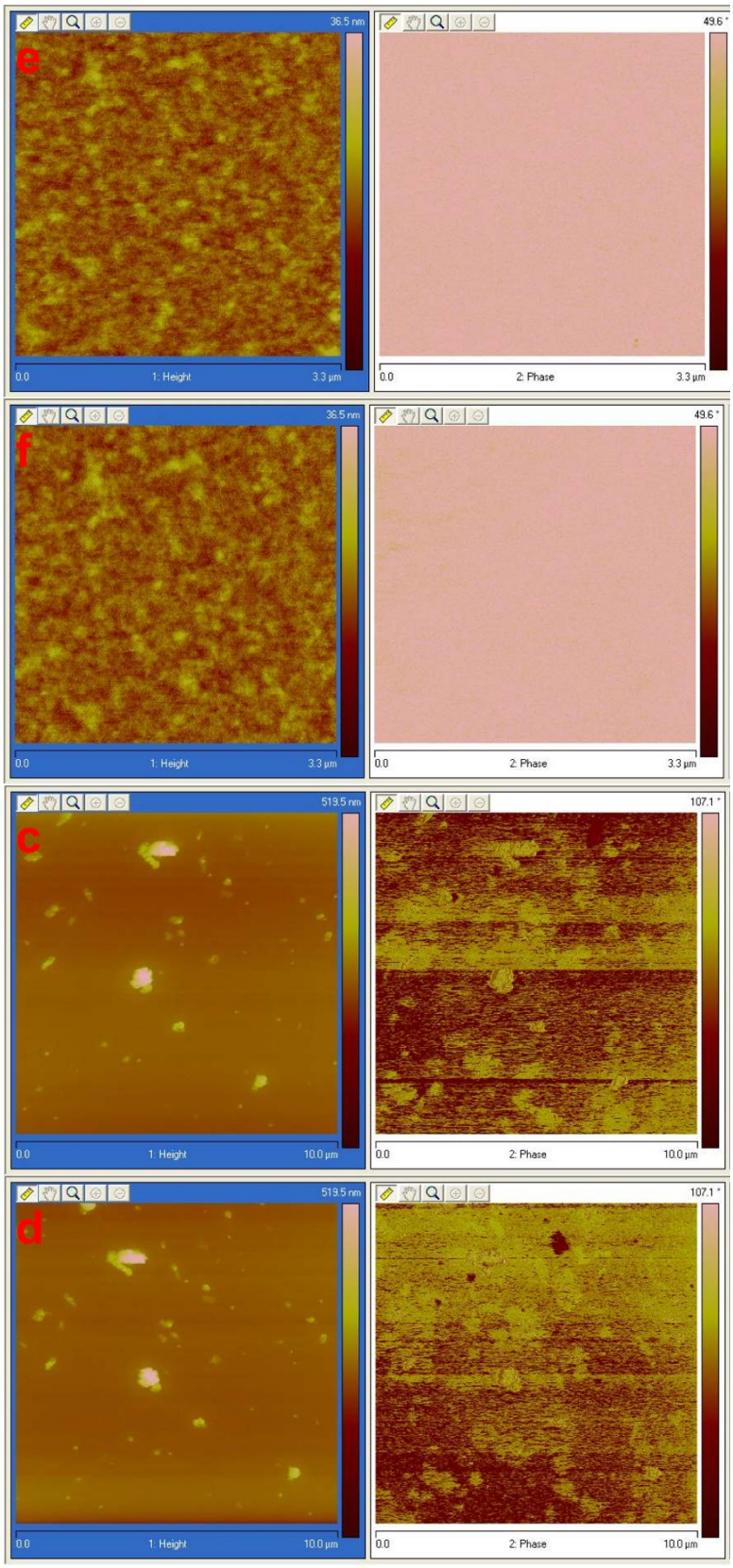

e
36.5 nm
0.0
1: Height
3.3 µm
49.6 °
0.0
2: Phase
3.3 µm
f
36.5 nm
0.0
1: Height
3.3 µm
49.6 °
0.0
2: Phase
3.3 µm
c
513.5 nm
0.0
1: Height
10.0 µm
107.1 °
0.0
2: Phase
10.0 µm
d
513.5 nm
0.0
1: Height
10.0 µm
107.1 °
0.0
2: Phase
10.0 µm

Fig. S4. AFM image. a hybrid of P3HT with 60 wt% ZnO before exposure to NO_2; b after exposure to NO_2 of a; c hybrid of P3HT with 60 wt% GO before exposure; d after exposure of c; e hybrid of pure P3HT before exposure; f after exposure of e.

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Biography-Yuhang Yang

Yuhang Yang was conscious that energy material is crucial in detecting and controlling pollution and saving energy. Therefore, he chose Prof. Howard E. Katz as his advisor to learn thermoelectric and pollute gas sensor application when he became a master graduate of Johns Hopkins University. Based on his previous experiments experience of the synthesis of core-shell structure of metal oxide and graphene oxide (GO), Prof. Katz inspired his idea on fabricating ZnO@GO core-shell nanoparticles and hybridizing with poly(3-hexylthiophene) (P3HT) for thermoelectric application. It is seen that the GO has metallic properties, because GO has high conductivity but low Seebeck coefficient leading to low power factor which is the materials ability of exchanging heat to electricity or in the opposite way. However, this hybrid of P3HT and ZnO@GO didn't turn into satisfying thermoelectric materials. The hybrid is multifunctional materials applicable on many fields, specifically on NO2 gas sensor, since P3HT, ZnO and GO each compound can be used to detect NO2 gas. By means of observing conductance changes before and after exposure to NO2, it was demonstrated that the hybrid of P3HT with 60 wt% ZnO@GO composites exhibits 210% sensing response to 5ppm NO2 gas exposure for 5min at room temperature which is much higher than any single compound.

This is a unique experiment because this hybrid has the highest sensitivity among the reported materials under low concentration at room temperature on detection of NO2.

He operated research at Regenerative Medicine and Biomimetic Materials Institute of School of Materials Science and Engineering at Tsinghua University from the summer vocation of his junior year till graduation. In the first half year of research, he was mainly responsible for synthesizing MRT T2 contrast agent ferriferous oxide (Fe3O4) nanoparticles. When it came to choosing topic of his final thesis of college, he found that papers which are focus on bio-application of graphene oxide (GO) were rapidly increasing. After discussing with his advisor, he came up with the idea of encapsulating of Fe3O4 with GO. The goal of the experiments was to combine MR imaging, magnetic target and photo-thermal therapy in one composite materials, Fe3O4@GO. The experiments results are extraordinary.

Yuhang's initial passion for materials science came from his father who has been constantly engaged in this field for many years. After a series classes of materials science and participation in laboratory on designing experiments and characterizing, he realized that his passion and enthusiasm for materials science not only came from his family, but also from the depth of his heart. His dream is to be an outstanding materials scientist making human life better. Ph.D. study would help him focus more on science research and probe more thoroughly into material science.

Curriculum Vitae- Yuhang Yang

Birth location： Qiqihar ,China, Birth date: 6/5/1993

Objective

To obtain the Ph.D. Degree in Material Science or Chemistry

Educational Background

09/2011-07/2015 University of Science and Technology Beijing (USTB)

- Degree: Bachelor of Engineering Major: Material Science & Engineering
- Overall GPA: 85/100 Major GPA: 86/100

08/2015-12/2016 Johns Hopkins University (JHU)

- Degree: Master Major: Material Science & Engineering
- Advisor: Prof. Howard E. Katz Major GPA: A-

Research Experience & Main Projects

06/2014-12/2014 Controlled synthesis of Fe3O4 single crystalline spheres in one solvothermal system and their application in MRI

- Detected TEM. Prepared water-based nano rolling mill compound and determined tribological property.

03/2015-07/2015 Fabrication of Composite Fe3O4@GO and its Application in MRI and Photothermal Therapy

- Designed experiment. Characterize properties. Wrote final thesis. Made presentation of work.

11/2015-Now Hybrid of P3HT and ZnO@GO Nanostructured Particles as Chemical Sensor

- Fabricate ZnO nanoparticles and encapsulated it with GO. Evaporate gold on glass substrate. Spin coating on prepared silicon wafer and OFET sensing properties investigation. Drop cast on gold electrode substrate and characterize conductivity and seebeck coefficient.

Professional Skills

- National Computer Rank Examination Certificate C++ (Grade 2)
- C++, AutoCAD, Inventor
- SEM, TEM, XRD and AFM
- Agilent 4155C Semiconductor Parameter Analyzer (Conductivity Test)
- Keithley 2410-C 1100V SourceMeter, and Keithley 2400 SourceMeter (Seebeck Coefficient Test)
- Spin coating, operation of evaporator and glove box

Publications

- Hybrid of P3HT and ZnO@GO Nanostructured Particles for Increased NO2 Sensitivity

  First author and accomplished manuscripts, In Peer Review by Journal of Materials Chemistry C

Extra-curricular Activities & Awards

02/2014 Successful Participate, MCM/ICM

08/2013 National Meritorious Winner, The 6th National Student Social Practice

& Science Contest on Energy and Emission Reduction

04/2013 Meritorious Winner, Social Practice & Science Contest on Energy and Emission Reduction of USTB

2011-2013 Third-class Scholarship, People's Scholarship (Twice)

2011-2013 Outstanding Student Cadre (Twice)

Master Graduate Major Course Taken

- Thermodynamics of Materials
- Kinetics and Phase Transformation
- Polymer Chemistry and Biology
- Structure of Materials
- Fundamental Physics and Chemistry of Nanomaterials
- Material Science of Thin Film
- Chemistry of Material Synthesis